# Fire Resistant Fuel for Military Compression Ignition Engines

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During an Army research program in the mid-1980s, fire-resistant diesel fuel that self extinguished when ignited by an explosive projectile was developed. Chemically, this fire resistant fuel (FRF) was a stable mixture of diesel fuel, 10 percent water, and an emulsifier. The Army FRF program ended in 1987 without fielding this fire resistant fuel formulation. There were both technical and logistical reasons for this. Unconventional warfare experienced in Iraq and Afghanistan involving use of Improvised Explosive Devices (IED) has led the Army to restart the FRF program in an attempt to counter the increasing threat of fuel fires. Efforts are now underway to develop new Fire Resistant Fuel to reduce and/or eliminate both the initial mist fireball and any residual pool burning.

Vehicle operation and environmental conditions commonly cause the temperature of the fuel in the vehicles to rise above its flash point, thus making it more susceptible to being ignited. This elevated fuel temperature, when combined with an ignition source such as a ballistic penetration near the fuel tank or fuel line, significantly increases the potential for a catastrophic fuel fire. This paper will discuss some of the aspects and limitations of developing a fire resistant fuel water emulsion and how the use of JP-8, as intended by the single fuel forward concept, affects this development.

## Background

During an Army research program in the mid-1980s, fire-resistant diesel fuel that self extinguished when ignited by an explosive projectile was developed. This fire resistant fuel (FRF) was a stable mixture of diesel fuel, 10% purified water containing less than 50ppm dissolved solids, 6% emulsifier, and 6% aromatic hydrocarbon concentrate to aid in the solubility of the emulsifier(ref. 1).

Previous research, including the program headed by the Army in the 1980's, involved using a variety of approaches to reduce the flammability of fuel. These approaches evaluated emulsified fuel, halogenated additives, mist control additives, and water-in-fuel emulsions, the latter showing the most promise, for ground vehicle applications (ref. 1-2). In a water-in-fuel emulsion, water molecules are suspended in fuel by the hydrophilic end of a surfactant which has its hydrophobic end dissolved in the base fuel. This fire resistant fuel was a clear to hazy emulsion consisting of water, emulsifier premix (equal amounts of the emulsifier and an aromatic concentrate), and diesel fuel. This emulsion performed satisfactorily both in diesel and turbine engine systems and could be prepared in the field for availability as needed. Although this earlier version of FRF did not eliminate the initial mist fireball that occurs when a projectile impacts the vehicle, it significantly reduced the fuel fire threat by retarding the flame-spread rate and would self extinguish spilled fuel eliminating residual pool burning. The self-extinguishing characteristic resulted from the heat sink provided by the water, emulsified water on the surface of the fuel preventing fuel vaporization, and the released water vapor that concentrating at the surface of the fuel eliminating oxygen from the fuel.

By 1987, the urgency for the development of a fire resistant fuel had diminished which resulted in the reallocation of funding. Additionally, there were both technical and logistical reasons for this. Filter plugged caused by the fuel at low temperatures, and the purity of the water needed for ensuring a stable emulsion was considerably higher than the standard level typically generated by the Army’s water purification units were a few of the major technical hurdles that the FRF program was unable to clear. The logistical burden requiring the 12% additive solution to create the FRF was also an obstacle. Because of a combination of these problems associated with FRF further efforts to pursue this fuel were discontinued.

## FRF Development Project

With the start of the conflicts in Iraq and Afghanistan, attention once again returned to the fuel fire threat that was taking its toll on both vehicles and personnel. The Army uses JP-8 aviation fuel in ground vehicle operations during combat situations as intended by the single fuel in the battlefield policy, as directed by DoD Directive 4140.43 titled "Fuel standardization," which mandates the use of JP-8 for air and ground forces. The shift to JP-8 enabled the Air Force and the Army to standardize on one single fuel for all operations. While the Air Force made this move, among other reasons, to increase safety by moving away from JP-4, the Army’s move to utilize JP-8 was a move toward a more volatile fuel, with a lower flashpoint than Diesel 2 fuel that was used previously.

JP-8 is a kerosene-based fuel containing a distribution of hydrocarbons with between 8 and 16 carbon numbers and having a minimum flashpoint of 38°C (100°F) (ref. 3). Diesel by comparison is a distillate fuel composed of a mixture of hydrocarbons with between 12 and 21 carbon atoms per molecule giving it a minimum flashpoint temperature of 52°C (125°F) (ref. 4). The flashpoint and light end components difference between diesel and JP-8 has become a large obstacle to overcome in the development of a fire resistant JP-8 formulation that will self extinguish when the fuel temperature is elevated to desert conditions, 65°C (149°F). The higher volatility of the JP-8 fuel when ignited at desert conditions, allows for a higher proportion of the fuel to be ignited which prevents the water emulsion from extinguishing the fire.

The U.S. Army uses compression ignition (diesel) engines to power a large majority of the ground vehicles in both its tactical wheeled and combat vehicles fleets. Most of these engines utilize fuel as a cooling agent for the engines fuel injector system and have a fuel delivery system that returns a portion of the fuel from the injectors back to the fuel tank. This recirculation heats the fuel, commonly raising the temperature of the fuel in the tank above its flash point, the lowest temperature that the vapor above the fuel will ignite when exposed to an ignition source, making the fuel more susceptible to being ignited.

The heating of the fuel used in compression ignition engines, when combined with any direct or indirect ballistic penetration near the fuel tank or fuel line, significantly increases the potential for a catastrophic fuel fire. Having a fuel that would not ignite under these conditions would have obvious benefits in terms of both increased personnel and vehicle survivability.

In April 2007, a more comprehensive effort was initiated that involved the following tasks:

- developing new emulsified fuel formulations;
- investigating mist control additives to diminish the fuel mist fireball;
- determining the effect of FRF on vehicle and equipment systems;
- designing a blending system for producing the FRF in the field;
- determining overall effectiveness of the FRF based on JP-8.

Initially a new baseline had to be established (for blending and flammability) using JP-8, as the previous work only evaluated diesel fuel. The development of an emulsified fuel formulation that yields a stable emulsion (i.e., one that does not separate) using JP-8 (or diesel fuel) has been the most difficult of all the above tasks. Variables such as fuel composition, aromatic content, water quality, emulsifier/surfactant chemistry, additive interactions, etc need to be understood and optimized. Adding to the complexity of this task is the addition of mist control additives (long chained, high molecular weight polymers) to the emulsified fuel formulation. The long chain polymers act to control fuel mist droplet size and thus reduce the size of the initial fireball that occurs.

This paper is meant to give an overview of the main development areas associated with formulating an optimal FRF. The areas include fuel fire resistance, equipment performance impacts, and also fuel stability and applications. Differences between a JP-8 and a Diesel 2 fuel will also be discussed. A more detailed report of the results is also available (ref 5).

## Results

Fire Resistance The vehicle fuel fires experienced in combat situations occur in two distinct phases. The first phase is commonly termed a fireball and seen as a fuel explosion. The fireball phase is caused by the explosive or ordnance rupturing the fuel tank and performing a rapid mechanical mixture of fuel spray and air mixture, which combined with the head from the explosive or ordnance manifests itself as an explosion. The second phase is the ignition and flame spread over the pool of fuel spilt on from the vehicles fuel tank. The pool fire is caused by the pool of fuel having a sufficient enough temperature to emit enough fuel vapors into the air above the pool surface to sustain a fire.

Due to the increased volatility of the JP-8 fuel when compared to diesel fuel it is imperative to suppress both phases of these fires as water alone has shown it is not capable of providing sufficient extinguishment, at acceptable concentrations of water, as was seen in the precursor work centered around diesel fuel. Therefore the goal of the development of a fire resistant JP-8 is to minimize both phases of these fuel fires.

Ballistic testing of different mist control additives incorporated into the emulsified fuel formulations was conducted. Figure 1 shows a side-by-side photo sequence of a regular JP8 and a diesel based FRF fuel. In order to simulate battlefield fuel tank conditions in a worst case/hot environment, the ballistic tests are being conducted with the FRF pre-heated to 150 deg F. A 55 gallon steel barrel filled with 30 gallons of FRF test fuel is used as the test article. The pre-heating and 25 gallons of vapor space simulate worst-case threat evaluation.

In the photo sequence in the left column, an untreated fuel displays typical fuel fire behavior exhibiting the initial fireball caused by the fuel mist explosion, the proceeds though the flame propagation stage of the pool fire to conflagration. Within a similar time frame, a FRF in the right column demonstrates a fire ball that is reduced in size by over 20%, and self suppresses preventing the flame propagation as seen in the untreated fuel.

While the pictures in Figure 1 show testing in a blast bunker, present testing is conducted in the open, where there are no “bunker effects” with respect to oxygen starvation or wind.

Column 1 Photo Sequence


Column 2 Photo Sequence


Figure 1. Conventional JP8 compared to Diesel FRF

In order to quantify the "fire resistance" effectiveness of a particular FRF formulation during ballistics testing, a data acquisition system is used to record temperature versus time measurements. The system consists of 10 thermocouples spread out linearly across the testing area (just above the 30 gallon steel barrel). Temperature response during testing is recorded at a logging rate of 5kHz for a total of 30 seconds. This information allows for the determination of the flame propagation rate and severity of the initial fireball and resulting burn where applicable. Figure 2 below shows a representative plot of an uncontrolled burn. Using this temperature and time data, work is underway to evaluate optimal FRF formulations exposed to various threat types.

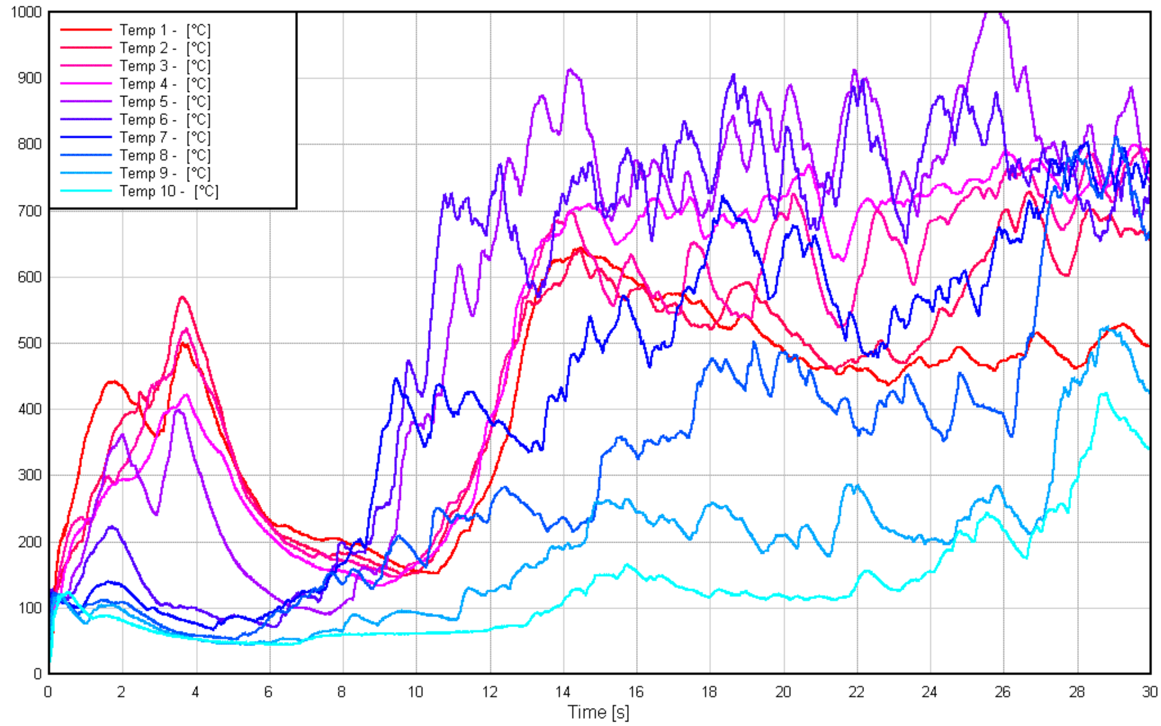


Figure 2. JP-8 Ballistic Test – Uncontrolled Burn

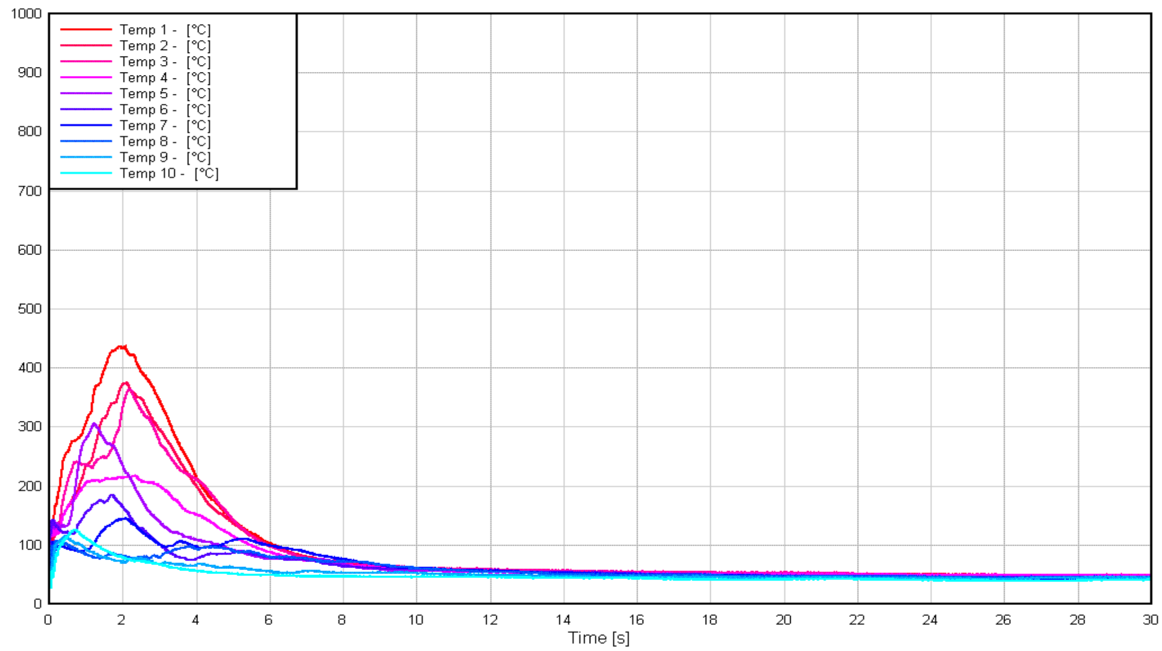


Figure 3. Diesel 2 FRF Ballistic Test – Controlled Burn

Figure 3 is a representation of FRF, in this case a base fuel of Diesel 2 was utilized.. Note the initial fireball caused by the explosive ordnance, temperature spike and time duration can be quantified.

To combat the fireball phase fuel formulation work continues to evaluate the mitigation properties of several mist control additives. The long chain polymers act to control fluid droplet size by imparting non-Newtonian properties into the fuel which decrease the surface to volume ratio and thus reduce the size of the initial fireball that occurs. Testing showed that these additives were able to reduce fireball effects by: reducing temperatures over 100°C, reducing fireball duration from over 2.5 seconds to 1.5 seconds, and an average 16% reduction in fireball size. These long chain, high molecular weight additives can reduce the initial fireball thelarge molecules will shear down when exposed to the high pressure injection systems of modern diesel engines that re-circulates a portion of the fuel back to the vehicles fuel tank, reducing effectiveness as the vehicle completes its mission. Engine testing demonstrated that mist control additive will degrade with successive passes through the engine fuel system. While the degraded polymer is still 1-3 orders of magnitude higher in average molecular weight that fuel molecules, its efficacy as a mist control additive is certainly reduced. Research is underway to todevelop polymer mist control additives that will be resistant to shear.

After the initial fireball, the water emulsion works to extinguish the fuel pool fire by means of the heat sink, prevention of fuel vaporization, and elimination of oxygen as described earlier. The mist control additives do not provide any fire suppression properties in the fire pool phase. Because JP-8 is already at a power disadvantage, in terms of vehicle performance, when compared to Diesel 2, formulating in only “just enough” water is a critical design criteria.

The JP-8 base fuel used in the formation of the FRF has a significant impact on the ability of the fuel to self extinguish. The JP-8 fuel specification (MIL-DTL-83133F) calls for a minimum flashpoint from 38°C, but can range up to the high 60’s. Depending upon the refining process used to make the fuel, the flash point will vary within this range. Because of the wide range of acceptable JP-8 flashpoint temperatures, the FRF formulation must be designed to perform on the lowest flashpoint fuels encountered. Utilization of a base fuel with as high of a flashpoint as possible allows for greater extinguishment characteristics to be imparted.

<u>Equipment Performance Impacts</u> Engine dynamometer testing was done using multiple engine families commonly used in Army vehicles. Shown below is data derived from the GEP 6.5L(T) engine. Testing was conducted to look at engine horsepower, torque and fuel consumption. The following three charts show the engine performance effects experienced by utilizing JP-8 FRF based fuels. In summary, it can be seen that the addition of water to the JP-8 fuel lowers the maximum torque and horsepower while increasing fuel consumption. This is not unexpected as any addition of water to the fuel lowers the overall energy content of the fuel. The mist control additive does add a very small amount of energy back into the fuel, but it is nearly negligible.

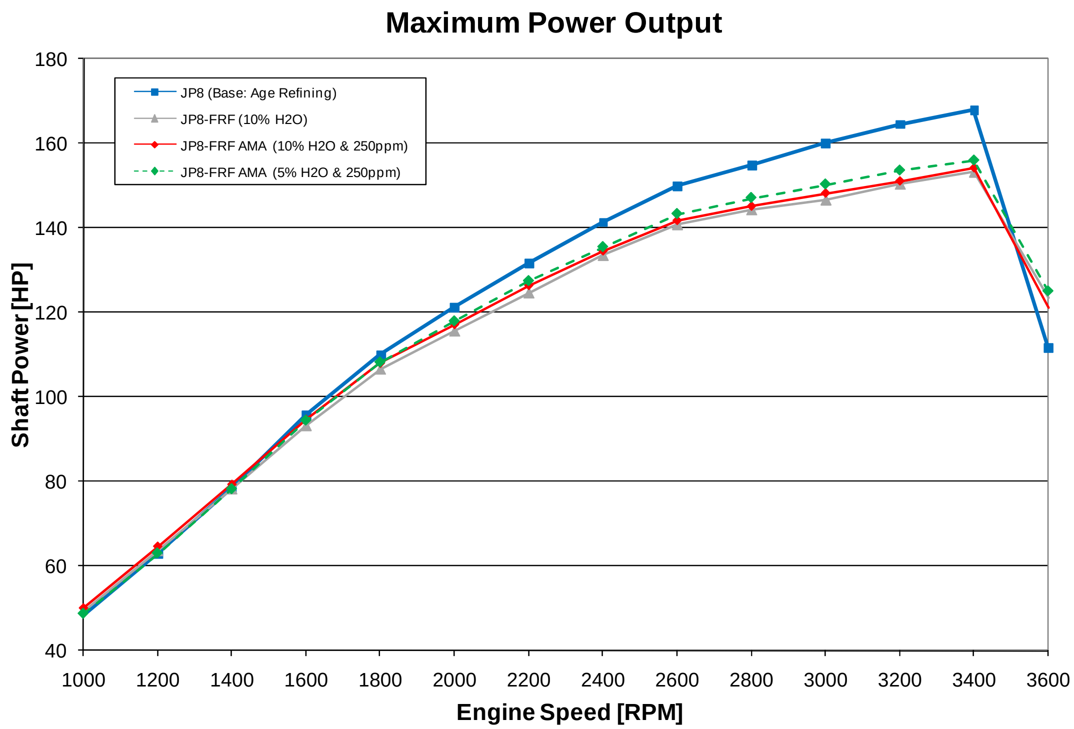


Figure 4. 6.5L Turbo Diesel Maximum Power Output

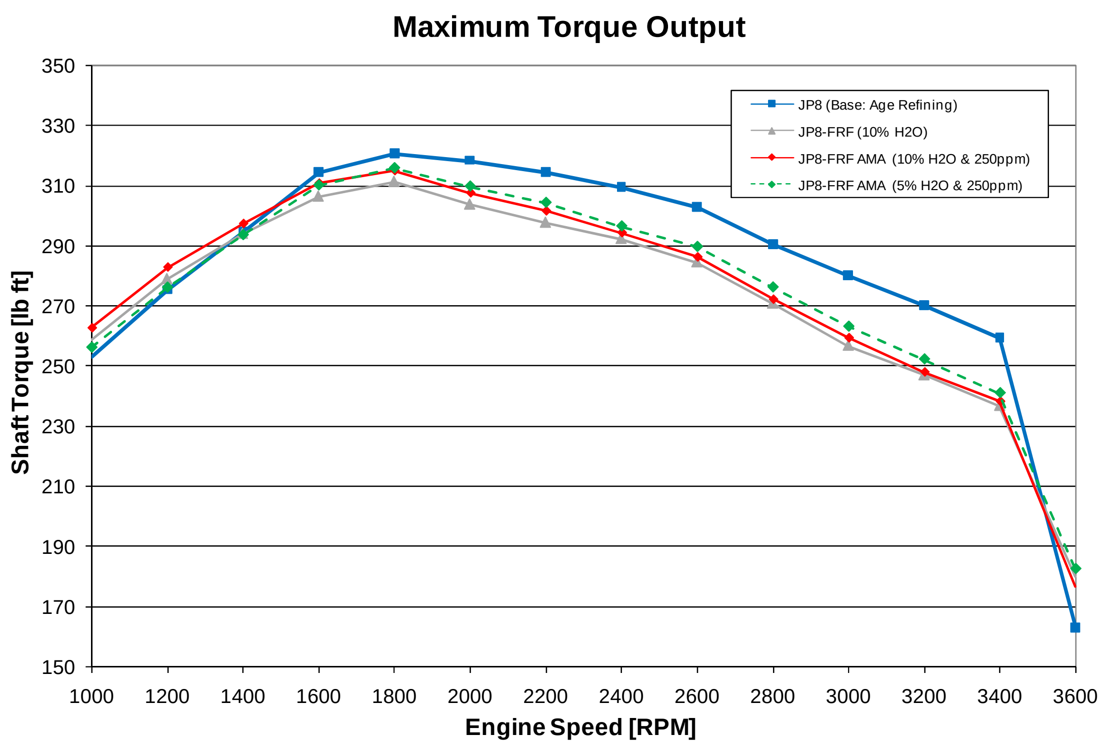


Figure 5. 6.5L Turbo Diesel Maximum Torque Output

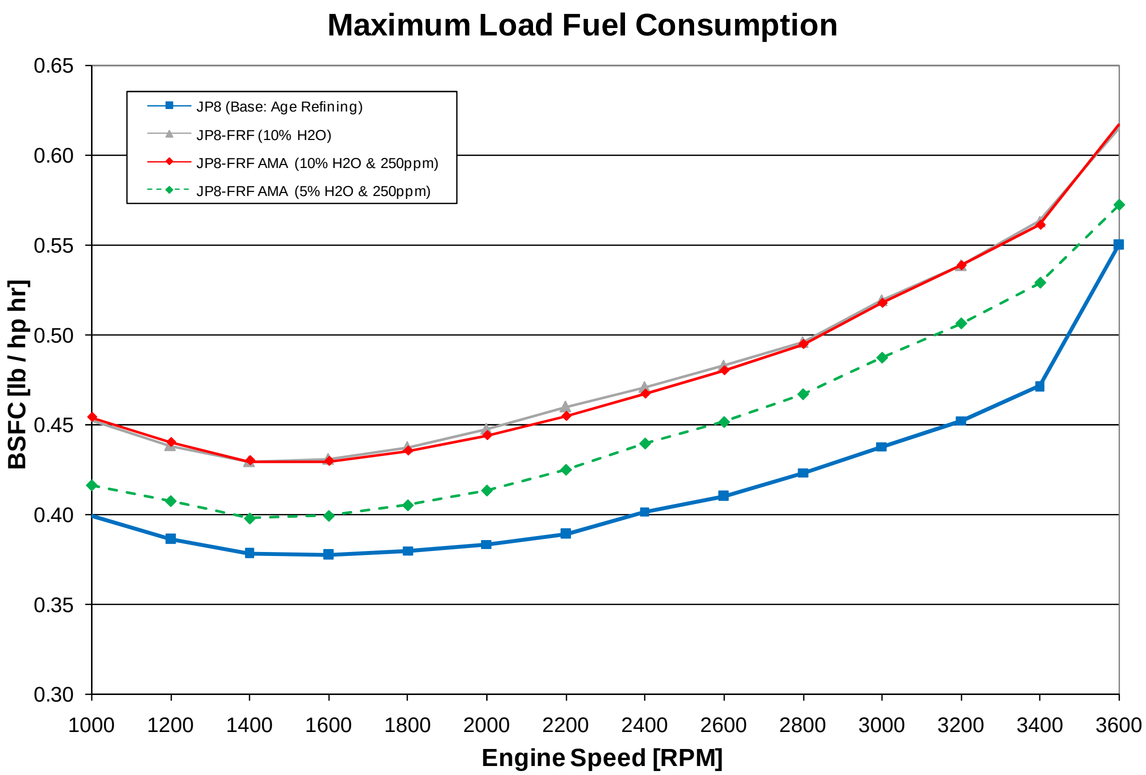


Figure 6. 6.5L Turbo Diesel Brake Specific Fuel Consumption

From the above charts, a FRF based fuel with 10% water, 250 ppm mist control additive would be expected to provide roughly 8-9 percent less power, torque and fuel economy than neat JP-8.

Engine data was used in existing vehicle models to provide a prediction to the effects of the FRF impacts on overall vehicle performance. The models showed that vehicle response to be minimal, it would be expected that individual vehicle operators may not notice the difference in fuel energies. Table 1 details the loss in acceleration and vehicle to speed on a flat surface, while Table 2 details the loss in speed on a slope.

| | JP8 | JP8 FRF |
|---|---|---|
| 0-30 mph (s) | 11.5 | 12.52 |
| 0-50 mph (s) | 32.24 | 37.87 |
| Top Speed (mph) | 67 | 61 |

Table 1. Simulated data for acceleration and vehicle to speed on a flat surface.

| | JP8 | JP8 FRF |
|---|---|---|
| 5% grade (mph) | 40 | 37 |
| 20% grade (mph) | 11 | 10 |
| 40% grade (mph) | 8 | 7 |
| 60% grade (mph) | 5 | 4 |

Table 2. Simulated data for vehicle to speed on a slope.

FRF Fuel Stability and per use Mixing  After a comprehensive initial evaluation of available fuel emulsifiers, testing was conducted on a refined list of emulsifiers to find those that will produce a stable emulsion with water using a range of both diesel and JP-8 fuels. Special care was taken to insure that the candidate emulsifiers were not as sensitive to water quality as in the prior project work.

Emulsions can be broadly segregated in two groups, micro and macro emulsions. These groups differ by the size of the suspended water droplets. Most of the emulsions presently being evaluated are in a class known as “micro-emulsions” due to the increased stability experienced with this type of emulsion. These mixtures are clear and bright. See Figure #7 below.

Figure 7. FRF Mixtures - Clear

Some FRF emulsions do not always remain clear/transparent, but rather appear white and milk like. See Figure 8 below. The functional performance of a non-stratified opaque FRF mixture is equivalent to clear FRF.

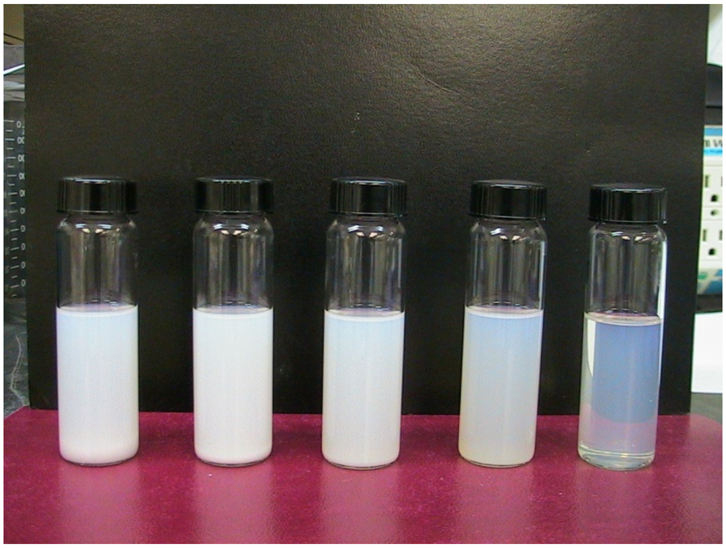

Figure 8. FRF Mixtures - Cloudy

For this effort, emulsion stability is defined by the absence of any distinct layers in the FRF mixture. Testing is underway to statistically optimize and quantify FRF emulsion stability. Variables include: temperature (hot or cold), base fuel, amount and type of emulsifier, amount and quality of water, and amount and type of mist control additive. This testing includes extended hot and cool storage, material compatibility studies and eventually temperature cycling. It should be noted that some stratified samples re-mix with minor agitation, but most do not.

Indefinite emulsion stability is desired, but not likely. Therefore, with limited stability and operational use limits, the present expected deployment is FRF blending at re-fueling points that fuel vehicles involved in high threat missions. The requirements for this preliminary design were to maximize use of existing Army petroleum and water handling equipment already available within the inventory. Different configurations of the necessary pumping and mixing equipment were considered, as detailed in Figure 9. However, use of a dedicated pump per fluid (i.e., water, fuel, and emulsifier/additive) that forces each through a static mixer were also evaluated and eventually adopted.

At the onset of this project, one of the goals was to develop a formulation that would produce a stable FRF with water that had up to 1000 ppm of dissolved solids. Initial attempts to meet this goal centered on finding an emulsifier that would produce the desired results. Unfortunately, none of the emulsifiers that we evaluated were found to produce an acceptable emulsion with water containing 1000 ppm solids. After an emulsifier was selected, we looked for alternative ways to reach the water hardness goal. Variations of mixing time and energy were investigated without success. Looking for yet another approach, we decided to mix a chelating agent (ethylenediamine tetraacetic acid, EDTA) with the blend. The EDTA chelates the solids and prevents them from inferring with the emulsifier. Through a series of experiments, we found that adding EDTA at a 1:1 ratio, on a ppm basis with the measured solids in the water, yielded a stable emulsion. We obtained acceptable results up to 1250 ppm of dissolved solids. We did not attempt mixing with water above 1250 ppm solids.

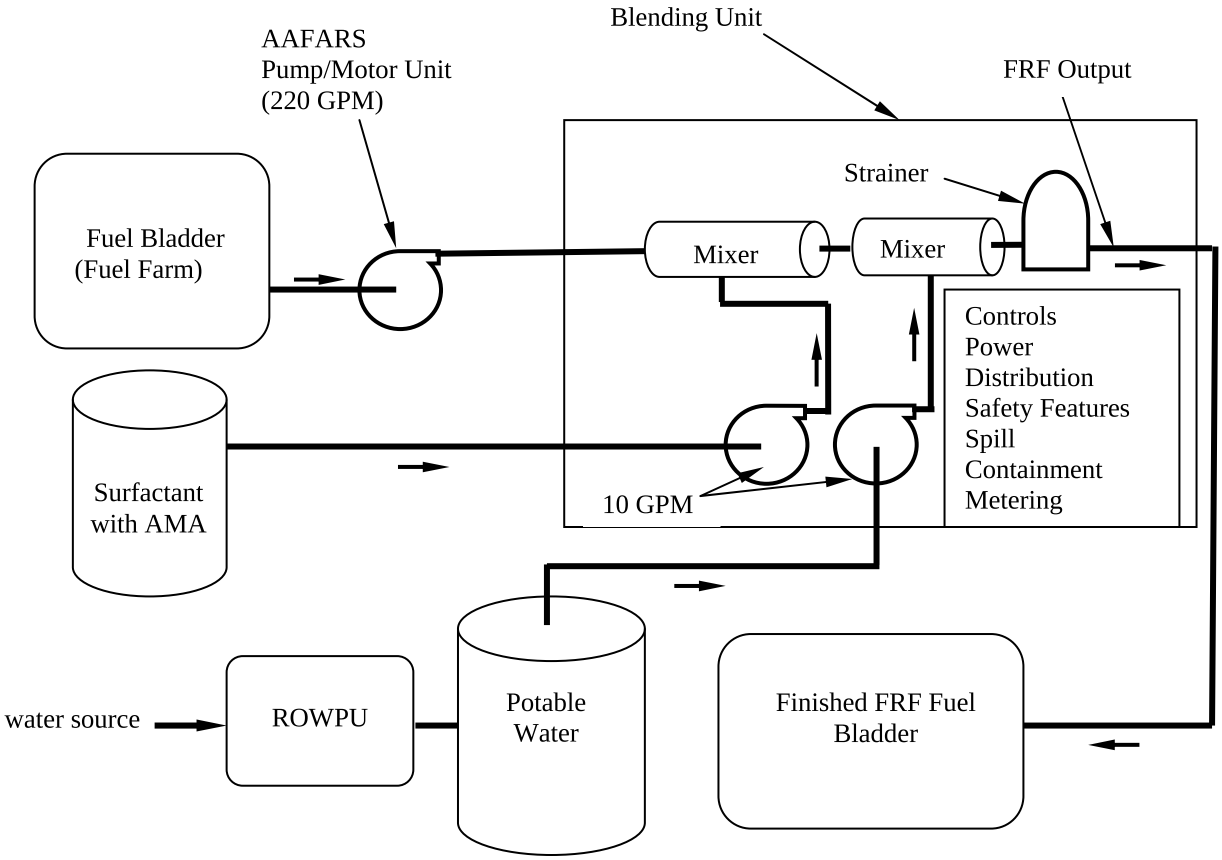


Figure 9. Preliminary FRF field blending concept diagram

Discussion

The Army's utilization of JP-8 aviation fuel for ground fuel applications has a tremendous impact on the development of a fire resistant fuel. The low flashpoint of the JP-8 results in requiring the FRF to control both the fireball and pool fire phases of vehicle fuel fires to be considered successful. Utilization of higher flashpoint base fuels increases the ability of the FRF to be able to self extinguish.

While desirable for FRF to have no performance impacts on vehicle operation, the data produced within this research program has provided similar results as previous FRF research programs. While power and range losses are undesirable, they are unavoidable and expected as any addition of water to the fuel lowers the overall energy content of the fuel. While the drawbacks of these effects may preclude the use of FRF in all ground vehicles at all times, there may be appropriate times when commanders would see benefits in the use of FRF. Utilization of a base fuel with greater energy density will offset the power loss experience by FRF JP-8.

Indefinite FRF stability is greatly desired, but the utilization of water in fuel emulsions makes it impracticable at this time. Efforts are being made to increase the stability of FRF fuels and make them usable across a greater range of environmental applications. But is not realistic that FRF can be developed that will be useable in all regions of the world.

Summary, Conclusions and Recommendations

The difference in flashpoint and light end components between diesel and JP-8 has become a large obstacle to overcome in the development of a fire resistant JP-8 formulation that will self extinguish when the fuel temperature is elevated to desert conditions, 65°C (149°F). JP-8 is a kerosene-based fuel having a minimum flashpoint of 38°C (100°F) while diesel No. 2 fuel by comparison is a distillate fuel with a minimum flashpoint temperature of 52°C (125°F). The higher volatility of the JP-8 fuel when ignited at desert conditions, allows for a higher proportion of the fuel to be ignited which prevents the water emulsion, traditionally used in fire resistant fuel, from extinguishing the fire.

FRF blends made with higher flash point fuels (diesel fuel) performed consistently better in emulsion stability and flammability testing compared to blends made with lower flashpoint fuels such as JP-8. Diesel fuel based FRF is available today, with above identified issues, but JP-8 based FRF needs further work.

Low-temperature stability of emulsions continues to be a concern. Some emulsions, depending on fuel and water quality, maintained stability to several degrees below 0°C. But most emulsions tended to break at about this temperature. We were able to recombine the components with minimal mixing but the emulsion did not have the same, typical, clear appearance as emulsions prior to freezing.

Under the right environmental conditions fire resistant fuel could be used in all of the Army's ground vehicles and support equipment, or just vehicles that are used in high risk operations where exposure to IEDs is high.

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